Observation of Instabilities in the ELETTRA Storage Ring

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Abstract

In order to reach the high brilliance of the light, ELETTRA has been designed for small emittances and is operating at high beam currents normally in the multi-bunch mode, being exposed there to coupled bunch instabilities. For some time-resolved experiments, single bunch operation with short bunch lengths at a maximum current is requested, both requirements which enhance single bunch instability effects due to the high current density. Observation of instability effects in ELETTRA are presented.

1. INTRODUCTION

ELETTRA is the third generation synchrotron light source situated at Trieste (Italy). It is optimized for photon energies in the urtraviolet to soft X-ray region i.e for electron energies of 1.5 to 2.0 GeV. A high energy linac is used as injector. Since October 1993 the storage ring and the injector are under commissioning [1, 2]. A ramping procedure [3] has been implemented which allows storage ring energies from injection, which is currently performed at 1.1 GeV, up to the maximum energy of 2.3 GeV.

All instability investigations have been performed at injection energy, to enhance the effects due to the low energy, but also for operational ease, since frequent injections and changes in beam current are needed. Investigations on multi-bunch and single bunch effects are presented. Also collective ion effects have been observed that will however not be treated here [4].

In general it can be summarized that the theoretical predictions were somewhat pessimistic and that threshold currents could be surpassed practically for all the relevant effects considered here and that the commissioning of ELETTRA progressed without any major problems. In fact, just twelve days after the storage ring commissioning start (5th Oct 1993) the maximum accumulated current reached 216 mA with only one cavity in operation. This value was almost doubled on December 10th when 410 mA with two active cavities were stored and therefore the design specification of 400 mA was exceeded. On 7th May 1994 the current was brought to a maximum value of 530 mA, with three cavities in operation and a 95% filling of the ring. In the same period single bunch currents larger than 50 mA were also reached.

2. MULTI-BUNCH INSTABILITIES

Multibunch instabilities are essentially driven by higher order modes (HOM) of the cavities. These HOMs were calculated before and then measured on a prototype cavity [5]. The analysis of their induced multibunch instabilities [6] have revealed that longitudinal instabilities have very low threshold currents, even below 1 mA, if the parasitic cavity mode is in resonance with a bunch mode. The more dangerous transverse multibunch thresholds are fortunately higher and there was apredicted 25% chance that ELETTRA could suffer from these. During operation it was successfully demonstrated that multibunch effects can be considerably reduced by changing the cavity temperature and therefore shifting the parasitic cavity modes, whereas the fundamental mode is reinstalled with a mechanical tuning system.

The cavity is a single cell unit with a smooth U-shape to prevent multipactoring. At the resonance frequency of 500 MHz the quality factor was measured to be Q = 40000 with a shunt impedance of about 6.9 MΩ, which translates into a ratio of effective shunt impedance and quality factor as R_{eff}/Q = 80.5 Ω. The bandwidth of the accelerating mode Δf=12 kHz becomes 60 kHz due to beam loading effects, implying that the impedance curve has an effective frequency width of some 100 kHz. The frequency tuning is achieved by means of an external mechanical tuner acting on the length of the unit [5]. The tuning range is approximately 200 kHz with about 800 Hz/μm, a speed of 200 Hz/sec and a relative frequency stability of $\pm 4\ 10^{-7}$ within this range. A fast phase control will be also used (currently under commissioning) with a response time of 5ms for 1° of phase variation. What, however, adds to the cavity flexibility is its additional tunability via temperature control. The working temperature of the cavity may be set in the range from 51 - 61°C while the frequency variation of the main harmonic is about 9 kHz/1°C compensated by the mechanical tuner. In this way the HOMs can be displaced with respect to the beam spectrum in order to avoid overlapping with adjacent bunch modes. A complete map of all HOMs as a function of cavity temperature was made during the commissioning [7]. The more relevant interactions of parasitic cavity modes with bunch modes are shown in Tables 1, 2. The first column indicates the beam harmonic $N = f/f_0$, and the four columns labeled with the cavity names (S2-S9) report the temperatures for which overlapping occurs with the unstable sideband of the bunch mode. The last column shows the instability current thresholds, taking into account the radiation damping at 1.1 GeV.

Table 1. Overlapping for Longitudinal Modes

N	HOM	S2	S3	S8	S9	Ith mA
821	L1	---	54.5	---	---	0.1
912	L2	---	---	---	57.8	5.
1227	L3	52.0	---	---	54.7	0.4
1229	L3	---	---	55.5	---	0.3
1308	L4	---	---	---	53.7	0.3
1382	L5	53.0	---	---	---	1.2
1623	L6	50.0	54.0	---	---	2.6

Table 2. Overlapping for Transverse Modes

N	HOM	S2	S3	S8	S9	Ith mA
644	D2 a,b	57.0	---	---	60.5	1.5
1055	D4 b	---	---	---	59.0	180.
1070	D5 a	58.0	---	---	57.8	2.7
1125	D6 a	---	---	55.0	---	10.
1352	D7 b	---	---	58.0	---	333.

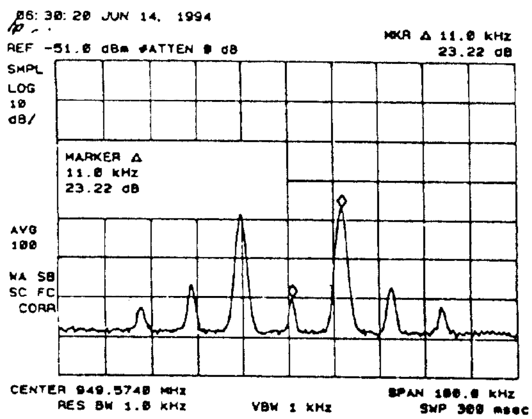

Figure 1. Spectrum of an excited longitudinal coupled bunch mode (n=821, I=1mA)

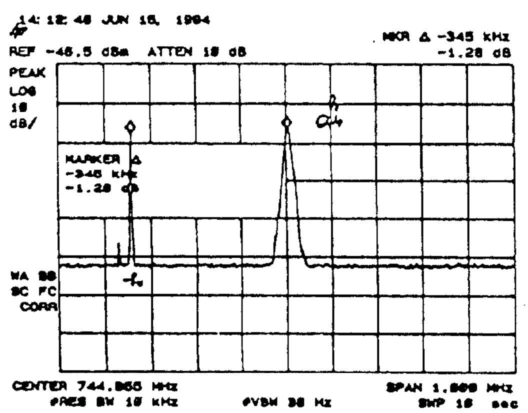

Figure 2. Spectrum of an excited transverse coupled bunch mode (n=644, I=40 mA)

The variation of parasitic mode frequencies was measured for all cavities. With the help of these measurements one can easily find for each cavity a temperature region where no overlapping occurs and the effect of multibunch instabilities is strongly reduced. Figure 1 shows the mode spectrum (with synchrotron sidebands) for a longitudinal parasitic mode which is in resonance with the sideband of bunch mode n=821. This was reached by tuning cavity S3 to 54.5°C, in accordance with Table 1. Figure 2 shows a transverse instability observed with a beam current of 40 mA when setting cavity S2 to 57°C and therefore close to the harmonic n=644. The fact that the threshold current is higher than predicted, indicates that other damping mechanisms are at work, such as Landau damping, which reduce the effect.

3. SINGLE-BUNCH INSTABILITIES

Single bunch instability thresholds are determined by the broad band impedance given by the beam environment. A low broad band impedance is needed in order to reach the design performance of the ring. An estimate of the impedance budget [8] revealed a longitudinal broad band impedance of $|Z/n|_0$=0.7-1 Ω. To be conservative, all instability calculations have been performed with an impedance of 2 Ω, leading therefore to a single bunch threshold of about 9 mA. The actual measurement of the impedance on the machine gave a value of 0.75 Ω which scales to á single bunch current of 24 mA (no Landau damping included). The actual single bunch current achieved in the machine was >50 mA.

Single bunch effects have been explored by measuring the bunch length as a function of current, the variation of the transverse tunes and the synchrotron tune with bunch current and the change in synchronous phase with increasing bunch current. All these measurements have been performed for different initial bunch lengths, i.e. different RF-voltages.

(i) Bunch length measurements have been performed by analyzing the bunch spectrum taken from a wide band pick-up with a 26 GHz spectrum analyzer and by looking at the stripline signal with a fast single shot digitizer with an analog band width of 4.5 GHz. Both measurements were done close to the ring with short cable connections to the devices in the ring, in order to reduce their effects on the measurement. The more reliable results have been found from the digitizer measurements, which are collected in the Figure 3, where the bunch length as a function of current is drawn in a normalized form for various RF-voltages.

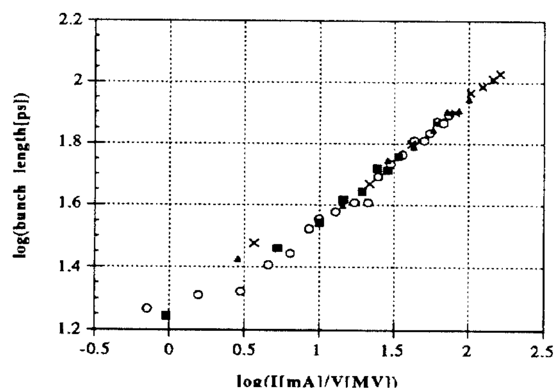

Figure 3. Bunch length versus current for RF-voltages of 0.35, 0.5, 1.0 and 1.5 MV (peak value)

At low current a threshold behaviour becomes visible, but not very pronounced due to the low measurement accuracy in this range.

Another convenient form is in the representation of the bunch length current relation as a function of the 1/3 power for the current, which for the turbulent regime should show a linear dependence. Figure 4 reports such a dependance for a RF-volatage of 1 MV.From the slope at higher currents, i.e.

longer bunches, the longitudinal broad band impedance can be derived from the criteria of the turbulent threshold:

$$\left(\frac{\sigma}{R}\right)^3 \geq \left|\frac{Z}{n}\right|_{eff} \frac{\sqrt{2\pi}}{h \cos \varphi\, F} \frac{I}{V_{RF}} \qquad (1)$$

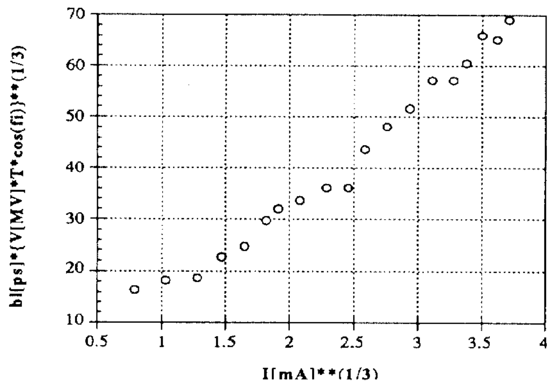

Figure 4. Bunch length versus current for VRF=1MV, showing the $I^{1/3}$ dependance in the turbulent regime

(ii) The transverse impedance can be extracted from measurements of the betatron frequency shifts with current. A measurement for 1 MV peak voltage is shown in Figure 5.

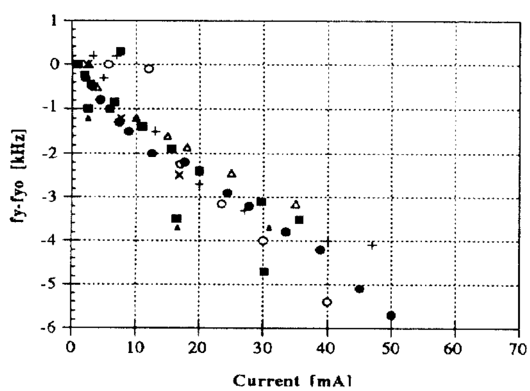

Figure 5. Variation of vertical tune with single bunch current

From the initial slope of a quadratic fit (Figure 5), the effective transverse impedance can be derived, by using the relation:

$$\left(\frac{df_\beta}{dI}\right) = \frac{f_0 R \beta}{2\pi \sigma E/e} Z_{T\,eff} \qquad (2)$$

At short bunch lengths the impedance is reduced due to the incomplete overlapping of the beam spectrum with the impedance curve. For a gaussian distribution the reduction is given by the relation $|Z_v|_{T\,eff} = 2(\omega_r \sigma_\tau)^2 |Z_v|_T$ where ω_r is resonance frequency of the Q=1 resonator model and σ_τ is the bunch length. For the measured bunch length at small currents, i.e. σ_τ=18.5 ps, the transverse broad band impedance becomes $|Z_v|_T$ =130 kΩ/m. By using the approximation $|Z|_T = (2R/b^2)\, |Z/n|_0$ for a circular geometry we can derive also the longitudinal impedance. For a cut off frequency of 2.2 GHz, corresponding to an effective radius b=23 mm, which is a reasonable value, we again find 0.75 Ω for the longitudinal broad band impedance.

No relevant variation of the horizontal tune and synchrotron tune with current could be observed.

(ii) Measurements of the synchronous phase angle shift with single bunch current have been performed for various RF-voltages. There from the bunch length dependence the loss factor can be derived which allows the derivation of the resonator parameters of the impedance model. Although the measurements roughly confirmed the previously mentioned values, they were not very consistent and therefore not sufficiently accurate to derive the resonator parameters.

No transverse mode coupling has up to now been observed although using the above results the estimated transverse mode coupling [9] threshold is found to be 40 mA. Some preliminary measurements on the head tail threshold as a function of the chromaticity were performed. For the m=0 head-tail mode the threshold current of 22 mA was found for ξ_v=- 0.3. Beyond this current the beam blows vertically up and starts to oscillate.

4. CONCLUSIONS

Multibunch instabilities in ELETTRA may be avoided by carefully choosing the temperature of the rf-cavities. The highest achieved multibunch current up to now was 530 mA.

The broad bunch longitudinal ring impedance is found to be $|Z/n|_0$=0.75 Ω while the transverse one is $|Z|_T$= 130 kΩ/m.

Using the measured values mode coupling is predicted for 40 mA but more than 50 mA bunch current could be stored in ELETTRA.

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